REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
17-08-2015	Conference Proceeding	-

4. TITLE AND SUBTITLE
Nonlinear Optics in Spatially Negatively Dispersive Metamaterials: Extraordinary andCounterintuitive

5a. CONTRACT NUMBER
W911NF-14-1-0619

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
Alexander K. Popov

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Purdue University
Young Hall
155 South Grant Street
West Lafayette, IN 47907 -2114

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
65605-PH.11

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Extraordinary frequency-converting nonlinear-optical propagation processes associated with backward electromagnetic and elastic waves are reviewed. Particular realizations of negative spatial dispersion which enable such waves are discussed

OUTLINE
* NIMs and BEMWs.

15. SUBJECT TERMS
Coherent nonlinear nanophotonics, metamaterials

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Alexander Popov
UU	UU	UU	UU		19b. TELEPHONE NUMBER 920-205-7474

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Nonlinear Optics in Spatially Negatively Dispersive Metamaterials: Extraordinary andCounterintuitive

ABSTRACT

Extraordinary frequency-converting nonlinear-optical propagation processes associated with backward electromagnetic and elastic waves are reviewed. Particular realizations of negative spatial dispersion which enable such waves are discussed

OUTLINE
* NIMs and BEMWs.
* Coherent NLO; exotic properties of energy exchange between ordinary and backward EM waves: greatly enhanced harmonic generation, frequency-mixing and optical parametric amplification.
* Spatial dispersion and BEMWs: phase matching of ordinary and backward EM waves in the carbon “nanoforest”: short pulses double back, tailoring pulse shapes.
* Backward-wave optical phonons and enhanced fs SRS.

Conference Name: Tri-Service Metamaterials Review

Conference Date: November 17, 2014

Meeting Agenda

ARMY Metamaterials Review Monday, November 17th 2014

ONR Metamaterials Review Tuesday, November 18th 2014

AFOSR Metamaterials Review Wednesday, November 19th

1330-1350 Trends on Materials in Antennas at ARL

Amir Zaghloul and Steven Weiss

Recent directions in improving the performance of conventional antenna designs focus on employing new materials. Metamaterials, metasurfaces, magneto-dielectrics and nano-technology materials have been introduced recently under different names with the general objectives of reduced physical dimensions and improved performance parameters. This talk reviews some of the developments in this area at ARL and identifies potential applications to improve the communications capabilities in Army systems.

1350-1410 Enabling Nanophotonics, Data Storage and Energy Conversion with New Plasmonic Materials and Metasurfaces

Vladimir M. Shalaev, Purdue University

We review our recent research on developing novel plasmonic materials (other than the metals used so far) that will form the basis for future low-loss, CMOS-compatible devices that could enable full-scale development of the plasmonic and metamaterial technologies. We replace metals in plasmonic metamaterials by new plasmonic ceramics such as transition metal nitrides, whose properties resemble those of gold. However, unlike gold, these materials have adjustable/tunable optical properties, they are cost-effective, robust, refractory (withstanding very high temperatures) and compatible with standard semiconductor processing. The new material platform as well as novel designs and concepts, including 2D meta-surfaces for nanophotonic devices, data storage and energy conversion will be discussed.

1410-1430 CONTROLLING SURFACE WAVES by METASURFACES

Stefano Maci, University of Siena

Metasurfaces constitute a class of thin metamaterials, which can be used from microwave to optical frequencies to create new electromagnetic engineering devices. They are obtained by a dense periodic texture of small elements printed on a grounded slab without or with shorting vias. These have been used in the past for realizing electromagnetic bandgaps (EBG) or equivalent magnetic-walls. Changing the dimension of the elements, being the sub-wavelength 2D-periodicity equal, gives the visual effect of a pixelated image and the electromagnetic effect of a modulation of the equivalent local reactance. The modulated metasurface reactance (MMR) so obtained is able to transform surface or guided waves into different wavefield configurations with required properties. The MMR allows a local modification of the dispersion equation and, at constant operating frequency, of the local wavevector. Therefore, the general effects of metasurface modulation are similar to those obtained in solid (volumetric) inhomogeneous metamaterial as predicted by the Transformation Optics; namely, re-addressing the propagation path of an incident wave. However, significant technological simplicity is gained. In this lecture, after illustration of the design method of metasurface antennas and transformation optics for surface waves,various examples are presented and discussed, including Luneburg lenses, Maxwell's Fish-eyes, isoflux antennas.

1450 1515 Structured light in the Meta-World

Natasha Litchinitser, University of Buffalo

We discuss fundamental optical phenomena at the interface of singular optics and metamaterials, including theoretical and experimental studies of linear and nonlinear light-matter interactions of vector and singular optical beams in optical metamaterials. Understanding the physics of the interaction of complex beams with nanostructured "engineered" media is likely to bring new dimensions to the science and applications of complex light, including novel regimes of spin-orbit interaction, extraordinary possibilities for dispersion engineering, and novel possibilities for nonlinear singular optics.

We show that unique optical properties of metamaterials open unlimited prospects to "engineer" light itself. For example, we demonstrate a novel way of complex light manipulation in few-mode optical fibers using metamaterials highlighting how unique properties of metamaterials, namely the ability to manipulate both electric and magnetic field components, open new degrees of freedom in engineering complex polarization states of light. We discuss several approaches to ultra-compact structured light generation, including a nanoscale beam converter based on an ultra-compact array of nano-waveguides with a circular graded distribution of channel diameters that coverts a conventional laser beam into a vortex with configurable orbital angular momentum and a novel, miniaturized astigmatic optical element based on a single biaxial hyperbolic metamaterial that enables the conversion of Hermite-Gaussian beams into vortex beams carrying an orbital angular momentum and vice versa. Such beam converters is likely to enable a new generation of on-chip or all-fiber structured light applications. We also present our initial theoretical studies predicting that vortex-based nonlinear optical processes, such as second harmonic generation or parametric amplification that rely on phase matching, will also be strongly modified in negative index materials. Here we predicted that second harmonic generation with structured light carrying orbital angular momentum and propagating in a negative index material results in a possibility of generating a backward propagating beam with simultaneously doubled frequency, orbital angular momentum, and reversed rotation direction of the wavefront. Finally, we discuss a macroscopic invisibility cloak, based on structured light, operating at optical wavelengths.

These studies may find applications for multidimensional information encoding, secure communications, and quantum cryptography as both spin and orbital angular momentum could be used to encode information; dispersion engineering for spontaneous parametric down-conversion; and on-chip optoelectronic signal processing.

1520-1540 Practical Nanophotonics with Plasmonic Ceramics

Alexandra Boltesseva, Purdue University

In recent years, two avenues of nanophotonics, namely plasmonics and optical metamaterials (MMs), have seen an explosion of novel ideas and designs that could provide breakthrough devices and exotic functionalities. However, the fields of plasmonics and MMs have long been dominated by noble metals, which lack both tunability of their optical properties and CMOS-compatibility. Plasmonic ceramic materials, such as transition metal nitrides and transparent conducting oxides (TCOs), offer a solution to these problems and could enable consumer photonic devices across

many fields including flat photonic components (lenses, wave-plates, spatial light modulators), localized surface plasmon resonance (LSPR) applications, integrated optical circuitry, and metamaterials-based light sources and solar cells. Among the transition metal nitrides, titanium nitride (TiN) has shown promise as a plasmonic material in the visible and near infrared. TiN is a plasmonic ceramic material having optical properties resembling those of gold. Unlike gold however, TiN is CMOS-compatible, mechanically strong, and thermally stable at higher temperatures. Additionally, TiN exhibits forms low-index surfaces with surface energies that are lower than those of the noble metals, facilitating the growth of smooth, ultra-thin crystalline films that are useful crucial in constructing low loss, many high-performance plasmonic and MM devices including waveguides and hyperbolic MMs (HMMs). Hyperbolic MMs have been shown to exhibit exotic optical properties, including extremely high broadband photonic densities of states (PDOS), which are useful in quantum photonics applications. We demonstrated that an epitaxial superlattice with TiN as a plasmonic component works as a high quality HMM that provides a higher PDOS enhancement than metal-based HMMs. We also showed that TiN is a successful material for integrated plasmonic applications, with waveguiding structures achieving surface plasmon polariton propagation lengths exceeding 5 mm. Such structures can easily be integrated with plasmonic modulators, which use the tunability of TCOs to attenuate a SPP wave. In this talk, various plasmonic ceramic materials will be discussed for nanophotonic devices with enhanced flexibility and performance across many avenues of nanophotonic research.

1540-1600 Control of Förster energy transfer in vicinity of metallic surfaces and hyperbolic metamaterials

Mikhail Noginov, Norfolk State University

Optical cavities, plasmonic structures, photonic band crystals, interfaces, as well as, generally speaking, any photonic media with homogeneous or spatially inhomogeneous dielectric permittivity (including metamaterials) have local densities of photonic states, which are different from that in vacuum. These modified density of states environments are known to control both the rate and angular distribution of spontaneous emission. In the present study, we ask the question whether the proximity to metallic and metamaterial surfaces can affect other physical phenomena of fundamental and practical importance. We show that the same substrates and the same nonlocal dielectric environments that boost spontaneous emission, also inhibit Förster energy transfer between donor and acceptor molecules doped into a thin polymeric film. This finding correlates with the fact that in dielectric media, the rate of spontaneous emission is proportional to the index of refraction n, while the rate of the donor-acceptor energy transfer (in solid solutions with random distribution of acceptors) is proportional to n-1.5. This heuristic correspondence suggests that other classical and quantum phenomena, which in regular dielectric media depend on n, can also be controlled with custom-tailored metamaterials, plasmonic structures, and cavities.

1600-1620 Nonlinear Optics in Spatially Negatively Dispersive Metamaterials: Extraordinary and Counterintuitive

Alexander Popov, Purdue University

Extraordinary frequency-converting nonlinear-optical propagation processes associated with backward electromagnetic and elastic waves are reviewed. Particular realizations of negative spatial dispersion which enable such waves are discussed

OUTLINE:

- NIMs and BEMWs.
- Coherent NLO; exotic properties of energy exchange between ordinary and backward EM waves: greatly enhanced harmonic generation, frequency-mixing and optical parametric amplification.
- Spatial dispersion and BEMWs: phase matching of ordinary and backward EM waves in the carbon "nanoforest": short pulses double back, tailoring pulse shapes.
- Backward-wave optical phonons and enhanced fs SRS.

1620-1640 Ferroplasmons: Localized surface plasmons in a ferromagnetic metal

Ramki Kalyanaraman, University of Tennessee

This talk will discuss a recent collaborative effort that lead to the discovery of strong plasmons in a ferromagnet, which we have termed ferroplasmons. Near field studies by high resolution electron microscopy revealed that ferroplasmons (FPs) exist in bimetallic nanoparticles, such as of Ag-Co. The Co region of the bimetal lights up with intense visible (and higher energy) localized surface plasmon resonances (LSPRs). Specific details of the ferroplasmon, such as its dependence on size, dielectric environment, and possible reasons for its origin will also be discussed. The talk will end with thoughts on some promising applications, such as design of better new sensing and magneto-optical material. We will also summarize some the challenges we are currently addressing.

1620-1700 Nonlocal homogenization of metamaterials and metasurfaces

Viktor Podolskiy, University of Massachusetts Lowell

Metamaterials and metasurfaces emerge as new powerful platform for controlling the flow of light with multiscale structures. Design and optimization of "meta-components" requires understanding of light interaction with complex composites that cannot be achieved with brute-force numerical solutions of Maxwell equations. In this work we demonstrate that optical properties of periodic plasmonic composites can be adequately modeled by nonlocal polarizability. The developed formalism provides insight into the origin of high-refractive index modes in hyperbolic metamaterials, predicts existence of new "dark" waves in nanowire composites, and provides a foundation for quantitative description of multiple refraction in metamaterials and metasurfaces, opening the door for design and optimization in meta-optics.

Dielectric Based Optical Metamaterials

Jason Valentine, Vanderbilt University

OBJECTIVES

- Fundamental studies of semiconductor-based metamaterials at optical frequencies for low-loss optics.
- Develop and demonstrate semiconductor-based 2D metasurfaces at optical frequencies.
- Develop and demonstrate semiconductor-based 3D metamaterials at optical frequencies.
- Investigate novel optoelectronic devices utilizing dielectric metamaterials and resonant crystals.

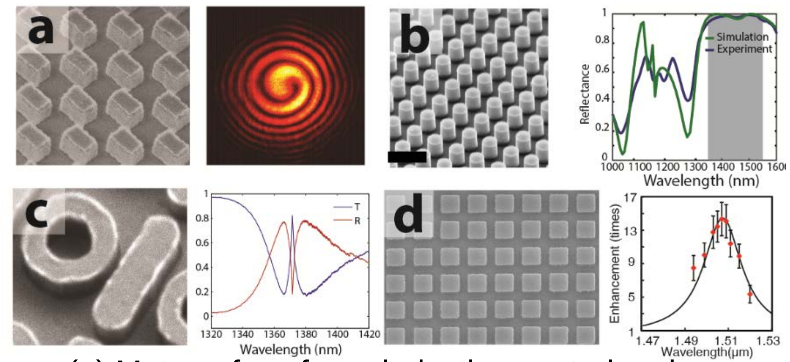


Figure: (a) Metasurface for polarization control and vortex beam generation. (b) Perfect reflecting metamaterial. (c) EIT metamaterial. (d) Fano-resonant 2D photodetectors.

APPROACH

- Use silicon and scalable CMOS fabrication techniques.
- Use resonances in Si-based metasurfaces to realize control over phase and polarization.
- Control magnetic and electric resonances to realize perfect reflection from ordered and disordered Si-based metamaterials.
- Utilize bright and dark mode resonances in Si-based metasurfaces to realize electromagnetically induced transparency (EIT)
- Use Fano-resonant devices for enhancing absorption in 2D materials for optoelectronics applications.

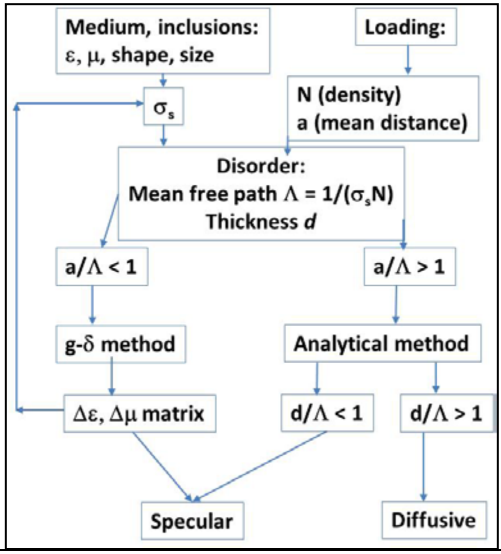
ACCOMPLISHMENTS

- Demonstration of highly efficient metasurface phase-plates (>98%)
- Demonstration of perfect reflecting (>99%) metasurfaces that are tolerant to disorder
- Demonstration of EIT metasurfaces with record high Q-factors (>480) and sensing figure of merit (>100).
- Demonstration of Fano-resonant crystal designs for realizing >80% absorption in graphene photodetectors, yielding a record high absorption enhancement of >14X.

Dielectric Metamaterials
Srini Krishnamurthy, SRI International

OBJECTIVES

- Theory development
  - Consider all-dielectric metamaterials (MMs) based on Mie resonances.
  - Consider analytical, semi-analytical, and numerical approaches.
  - Study the dielectric and optical properties of both ordered and disordered MMs.
- Proof of concept demonstration
  - Design MM with near-perfect reflection at1.55 μm
  - Fabricate periodic structure and measure reflection
  - Use results to advance theoretical development



The theory developed in this program is applicable to a number disorder regimes and can obtain both specular and diffused transmission through metamaterials as outlined here.

APPROACH

- Analytical methods
  - Maxwell-Garnet, Lewin, and Stroud/Pan models
  - Develop generalized effective medium model
- Semi-analytical method
  - Hybrid formulation of analytical and numerical
  - Include lattice-structure factor
- Numerical solutions with HFSS
  - Complements semi-analytic methods and confirms analytical solutions
- Disorder
  - Size disorder
  - Location disorder
- Demonstration
  - Ordered and disordered lithographic structures

ACCOMPLISHMENTS

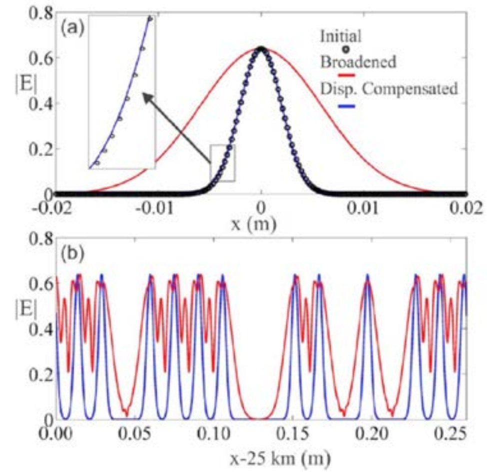
- Criteria of effective-medium and diffuse scattering regimes
- Developed and implemented modified g-δ method and new theory of local anisotropy
- Developed disorder theory in the effective medium
  - Size disorder: modified g-δ method
  - Location disorder: local anisotropy in permittivity and permeability tensors.
  - Resulted in new phenomenon and theory (alteration of reflection and transmission, birefringence, and rotation of polarization)
  - Agreement with experiment
- Developed analytical theory of diffusive scattering regime
- Two publications appeared and two manuscripts are in progress

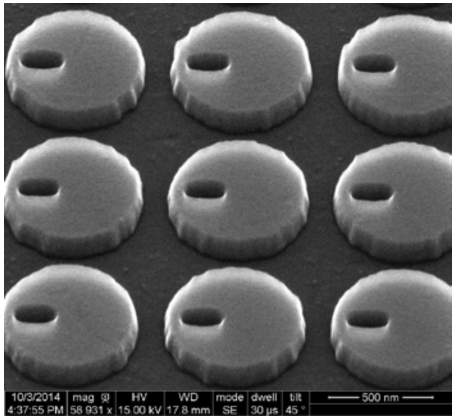
Dielectric Metamaterials with Low Loss and Tunability

C. M. Soukoulis, Iowa State University

OBJECTIVES

- Design novel dielectric resonators, reduce the losses and increase the operating frequency of metamaterials (MMs) with broadband capabilities.
- Tunable dielectric MMs with change temperature, stress and bias voltage/current. Achieve practical devices (sensing, absorbers/emitters, switches).





APPROACH

- State-of-the art computational techniques are essential to understand and design novel resonant structures of MMs
- Retrieval procedure to calculate both the real and imaginary of *ε, μ* and *n*
- Fabricate and characterize dielectric high-Q resonators MMs
- Tunable dielectric metamaterials: theory, numerical methods, experiments and characterization techniques.

ACCOMPLISHMENTS

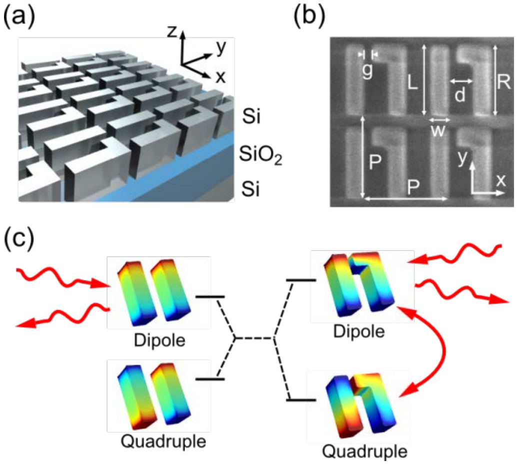
- Coupling metallic cut-wire with surface states of dielectric substrate. High-Q MMs
- Final results on pulse reshaping (dispersion engineering) (see left figure)
- Preliminary numerical results of negative *ε, μ* and *n* with high quality factors at infrared and optical wavelengths
- Design, simulations, fabrication, measurements of dielectric cylindrical disk with rectangular hole to give negative *ε* (see right figure above)

Tunable and Reconfigurable Spectrally-Selective Infrared Metamaterials with Ultra-Low Losses

Gennady Shvets, UT-Austin

OBJECTIVES

- Develop spectrally-selective Si based metasurfaces that can be used as emitters of circularly polarized thermal radiation
- Develop graphene-integrated active metasurfaces (MS) in mid-IR



(a) And (b): Fano resonant all-Si spectrally selective MS exhibiting extreme chirality. (c): The physics behind Fano resonance of the metasurface

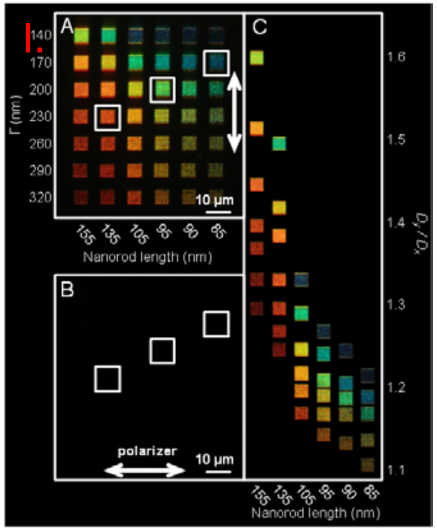
APPROACH

- Novel approach to high-Q MS using Fano resonant all-Si nanoantennas
- Novel experimental apparatus for measuring all 4 Stokes parameters of IR transmitted through the MS
- Design of super-chiral metasurfaces
- Design of double-Fano plasmonic MS integrated with backgated single layer graphene underneath the MS

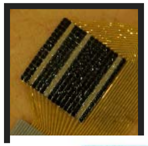
ACCOMPLISHMENTS

- Developed an all-dielectric metasurfaces with record-high quality factors Q>100
- Constructed an FTIR-based optical setup for rotating analyzer Stokes polarimetry at near normal incidence
- Made the first graphene integrated reflect-array with 10dB modulation

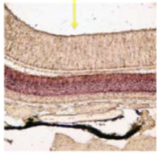
Biologically-inspired routes to sense-and-response in adaptive, intelligent metamaterials
PI: N. J. Halas, Rice (w/UIUC, MBL, UMBC)



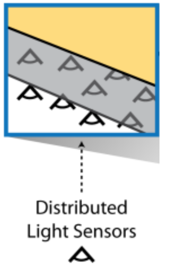
II.



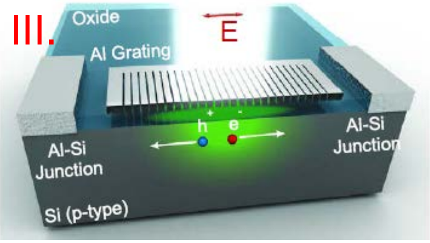
IV.



V.



III.



OBJECTIVES

- Discover ***underlying physical principles and mechanisms*** for active optical/metamaterials
- Advance our understanding of ***optical detection and recognition*** in cephalopods
- Develop ***concepts and mechanisms of compact optical detection*** to be integrated with active composite media for smart, responsive materials
- Design ***information architecture and algorithms*** for dynamic color and pattern change

APPROACH

- Use plasmonic clusters with variable interparticle distances to tailor the absorption and scattering of surface plasmon resonances
- Modulate the plasmonic response with liquid crystals, conductance variable substrates, and excitonic media
- Determine the architecture of cephalopod biophotonic skin elements and their operating principles
- Develop photodetectors with spectrally specific photovoltage generation for active tuning of plasmons
- Theoretically model experimental results and to predict novel plasmonic structures
- Design of a feedback-based information processing architecture based on distributed light sensors

ACCOMPLISHMENTS

I. Vivid, full color aluminum plasmonic pixels

II. Realization of general integration platform for sense-response materials

III. Fully Integrated Al Photodetector with Intrinsic Gain and Red-Green-Blue Selectivity

IV. Opsin and retinochrome identified in specific extraocular locations in *L. pealeii*, suggesting functional extraocular photoreceptors

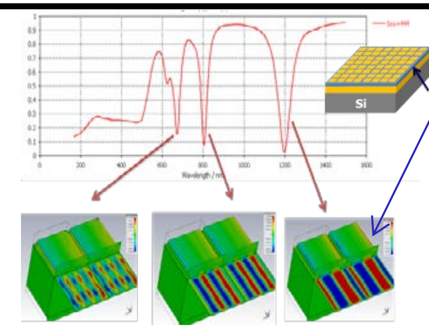
V. Sensor network architectures: image reconstruction with sensor networks

Spoof and Hybrid Spoof Metamaterials in the SWIR Spectral Region

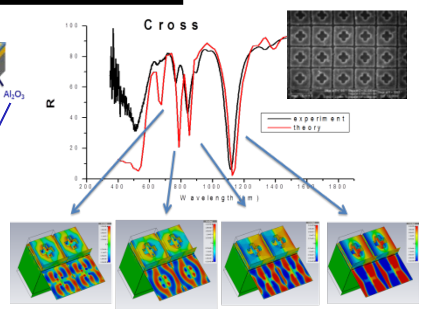
Orest J. Glembocki, Naval Research Laboratory

OBJECTIVES

- Determine the basic mechanisms behind the plasmonic activity of atomic layer deposited Ag
- Extend spoof-plasmons and hybrid-spoof plasmon systems into the near to mid-IR spectral range.
- Determine the implications of a dual band or overlapping band structure within a hybrid SPP-spoof plasmonic system



Simulations of surface plasmon polaritons in the visible to near IR show high field localization in ultra thin dielectrics.



Simulations and data for geometries that disrupt SPP's and localize fields around the geometry.

APPROACH

- Scale spoof geometries in Ag, ALD Ag, Cr and Au to near IR (1-2microns)
- Perform optical studies using reflection-transmission, and ellipsometry. The ellipsometry will allow us to obtain effective optical constants.
- Perform electromagnetic simulations using finite domain time dependence and finite elements to model the optical response and to establish the location of the high field regions.

ACCOMPLISHMENTS

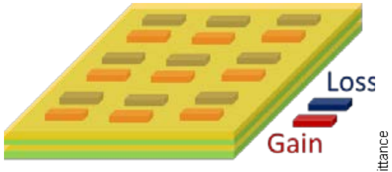
- Showed that very high quality resonators can be created in the visible and near IR using ultra thin dielectrics (15nm)
- Showed that SPP localization can be controlled through the used of embedded geometries in unit cells of periodic structures
- Showed that these geometries have weak dispersion, explaining gap resonances in random systems such as ALD Ag.
- These results have immediate impact for energy harvesting and detectors especially in ultra thin absorbers.

PT-Synthetic Plasmonic Metafilms with Coupled Gain-Loss Elements

Simin Feng, NSWC Dahlgren Division

OBJECTIVES

- Commercial Software are too slow. Develop a fast algorithm to design plasmonic metamaterials.
- Loss hinders applications of plasmonics. Explore novel EM properties related to balanced gain-loss parity-time (*PT)* synthetic plasmonic materials.



Super scattering
Amplify both transmission and reflection

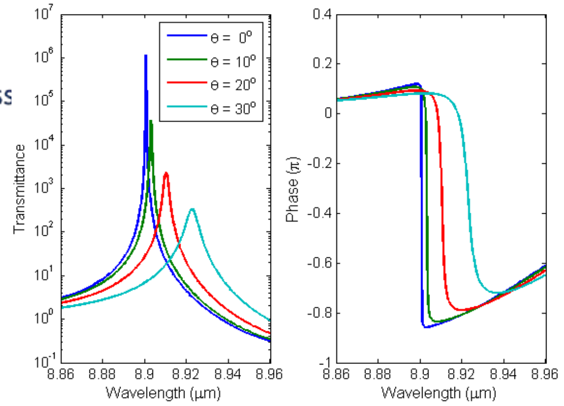


Figure 1: Left: Transmission; Right: Phase Shift

APPROACH

- Semi-analytical and numerical hybrid approach.
- Transfer and Scattering matrices

$$i\frac{\partial}{\partial z}\begin{pmatrix} E_t \\ \hat{z}\times H_t \end{pmatrix} = \widetilde{H}\cdot\begin{pmatrix} E_t \\ \hat{z}\times H_t \end{pmatrix},\quad \widetilde{H} = \begin{pmatrix} 0 & B \\ A & 0 \end{pmatrix}$$

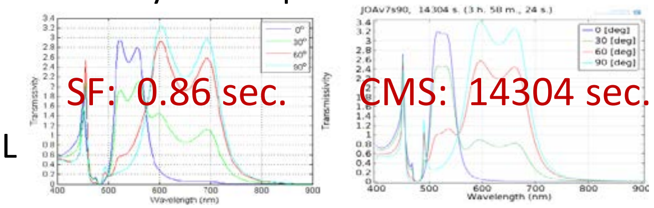
$$A = k_0\varepsilon_t\hat{I}_t + \frac{1}{k_0}\hat{z}\times\nabla_t\frac{1}{\mu_z}\hat{z}\times\nabla_t$$

$$B = k_0\mu_t\hat{I}_t + \frac{1}{k_0}\nabla_t\frac{1}{\varepsilon_z}\nabla_t$$

ACCOMPLISHMENTS

- Developed **a superfast algorithm** for designing certain plasmonic structures from visible to RF regions.
- **1,000 ~ 100,000 faster than COMSOL** (see Fig.2)
- Discovered dissipation-induced super scattering, super radiation, amplified transmission and reflection
- Patents: 3 patents submitted (provisional)
- Publication: Physical Review B **90**, 085411 (2014)
- Manuscript in progress: Dissipation-induced super scattering from *PT*-synthetic plasmonic metafilms

Figure 2:
SF: my Code
CMS: COMSOL

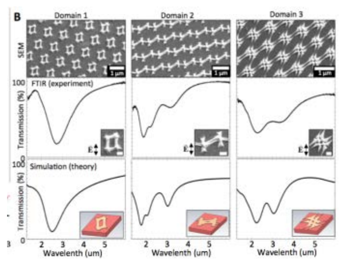


MURI: Large Area, 3D Optical Metamaterials with Tunability and Low Loss

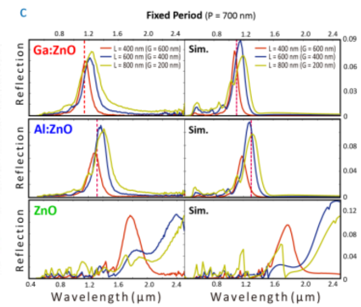
N. Engheta (PI, UPenn), A. Alu (UT Austin), A. Boltasseva (Purdue), C. Kagan (UPenn), C. Murray (UPenn), H. Mosallaei (Northeastern), V. Shalaev (Purdue), G. Whitesides (Harvard)

OBJECTIVES

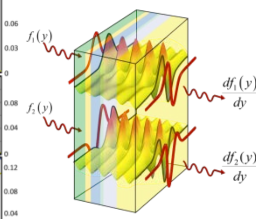
- To explore, model, and investigate the low-loss ENZ metamaterials for applications such as optical antenna applications
- To design, fabricate, experiment, characterize, model and analyze the metamaterials and metasurfaces for wave-front engineering
- To investigate other low-loss material building blocks for efficient light-matter interaction



Metasurfaces made using Shadow-Sphere Lithography



Nanoantennas over ENZ substrates



Metamaterial-based Analog Computing

APPROACH

- Efficient computational techniques suitable for massive computational domains including non-periodic, 3D, closely packed structures and materials
- A variety of nanofabrication techniques
- Use of suitable materials such as transparent conducting oxides, semiconductors, and noble metals
- Various characterization techniques
- A host of theoretical, analytical and numerical techniques

ACCOMPLISHMENTS

- Unusual performance of optical nanoantennas over ENZ substrates
- Ultrathin metasurfaces constructed using shadow-sphere lithography
- Giant nonlinearity using metasurfaces.
- Metamaterial analog computing
- Nanoimprinting of structures with nanomeshes, nanoantennas, nanoloops and nanorings.
- Digital Metamaterials.
- Solution processable/printable and thermo-switchable phase-change (VO2) films
- Plasmonically enhanced nanocrystal emitters

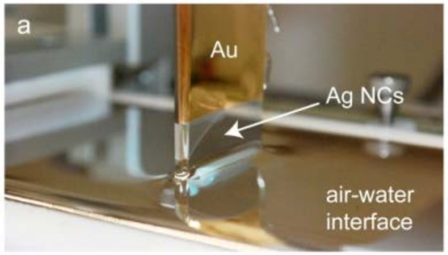
Polymer-Directed Nanocrystal Assembly for Fabrication of Large-Scale, Tunable Metamaterials

Andrea R. Tao, University of California, San Diego

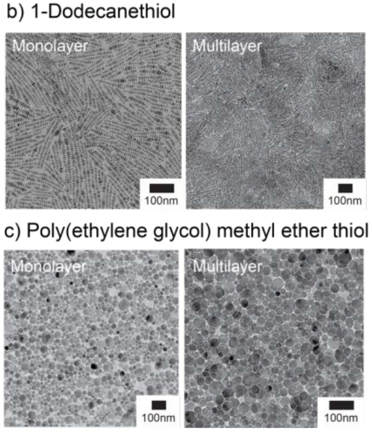
UC San Diego

OBJECTIVES

- Fabricate large-area, non-close-packed, plasmonic nanocrystal (NC) arrays with controlled morphologies
- Develop scalable methods for fabricating plasmonic nanojunctions and nanocomposites
- Investigate the adaptive optical response of metal and semiconductor NCs, and demonstrate utility as building blocks for metamaterials



(a) Photo of the NC assembly and dip-coating process. (b) Hydrophobic $Cu_{2-x}S$ nanodisks assemble into long stacks while (c) hydrophilic nanodisks assemble into "face-down" orientations at the air-water interface.



APPROACH

- Develop dip-coating technique for massively parallel NC assembly onto planar, flexible, or highly curved substrates
- Establish experimental phase diagrams for polymer-directed NC assembly with respect to polymer grafts, polymer matrix, and processing conditions
- Characterize NC diffusion rates within polymer and viscous matrices
- Synthesize highly-doped semiconducting $Cu_{2-x}S$ NCs using colloidal methods and assemble NCs into arrays and films

ACCOMPLISHMENTS

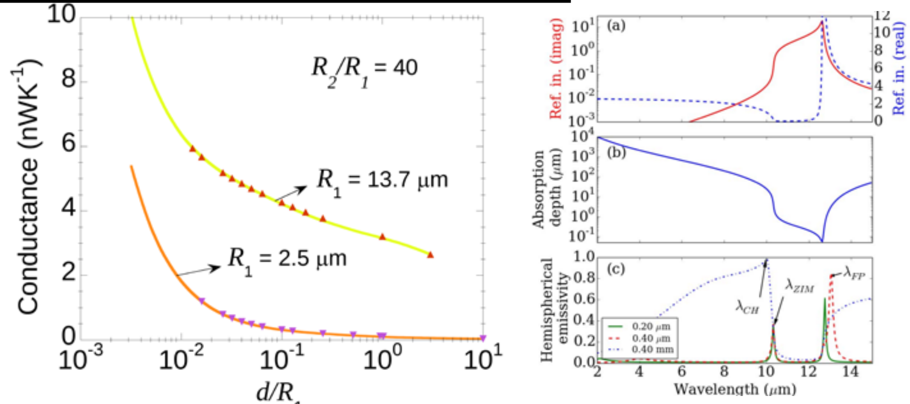
- Demonstrated NC assembly and dip-coating for the fabrication of ordered large-area NC arrays, absorbing metasurfaces, and near-field optical scanning probes.
- Developed image analysis software to provide statistical information regarding NC cluster size, morphology, and density; these data allow us to determine the assembly mechanism and diffusion rate of NCs in a polymer matrix.
- Successfully carried out oriented assembly of $Cu_{2-x}S$ nanodisks with controlled carrier densities
- First to demonstrate electromagnetic coupling in arrays of semiconductor NCs.
- 5 journal articles, 9 invited talks, 2 student awards
- Support for 4 graduate students, 1 post-doc, and 6 undergraduates; 2 M.S. degrees granted
- Awarded DURIP for acquisition of a Coupled Raman-Atomic Force Microscope System that will be leveraged for this work

Filtered near-field thermal radiation: Isolating surface phonon polariton resonances in near-field radiative transfer

Arvind Narayanaswamy, Columbia University

OBJECTIVES

- Probe exclusively role of surface phonon polaritons (SPP) on increase of radiative transfer at small gaps
- Prove (or disprove) that SPP contribution scales as *R/d* for energy transfer between a sphere and a plane
- Identify gap at which energy transfer saturates



Left: Latest numerical results showing agreement between exact numerical results and modified proximity approximation for unequal but homogeneous spheres. Right: Predictions of spectral emission from a polar thin film (SiC in this case) on Ag film emitter. Similar substrates with alumina thin films have been fabricated for this project.

APPROACH

- Experiment – measure *near-field contributions alone* with a bi-material cantilever as thermal sensor
  - Create substrates that allow only SPP radiative transfer
- Computational/theoretical: Dyadic Green's functions/vector spherical harmonics & proximity approximation
  - Develop robust methods capable of handling sphere/plane interactions
  - Modify Green's function method to handle coated substrates/spheres

ACCOMPLISHMENTS

- Computations extended to R_2/R_1 = 40 and d/R_1 = 0.016.
- Formalism changed to include coated spheres
- Substrates with polar thin films (alumina) fabricated.
- Prediction of selective thermal emission from substrates of the type we have fabricated.

Goals for next year

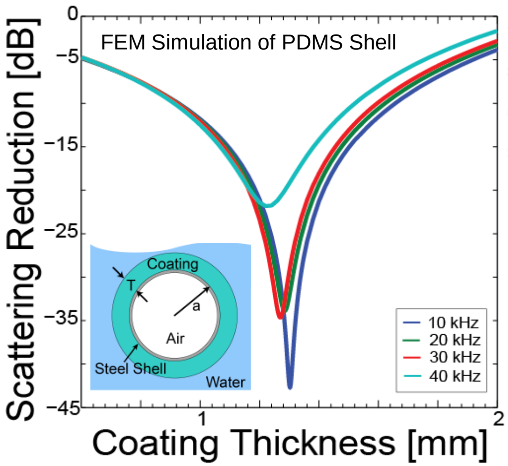
- Complete numerical code to analyze coated sphere radiative transfer with new formalism
- Perform near field experiments with alumina/sapphire spheres and newly fabricated substrates

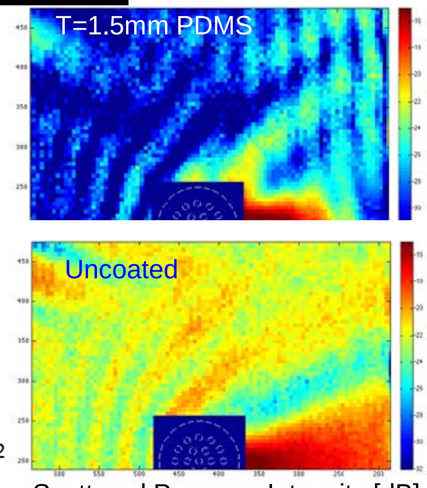
Long Wavelength, Aqueous Cancellation Coating

Gregory Orris, Naval Research Laboratory

OBJECTIVE

- Reduce long-wavelength scattering cross-sections of hollow steel cylinders in aqueous environments over a broad range of frequencies through monopole scattering cancelation with thin, low-shear elastic coatings.





APPROACH

- FEM and MST modeling of parameter space to establish coating thickness baselines for experiments
- Construction of precise thickness, PDMS coatings for quasi-2D experiments
- Construction of long, coated cylinders using commercially available silicone rubber
- Collection of acoustic scattering data in NRL water tank facility
- Refinement of coating thickness using modeling feedback loop

ACCOMPLISHMENTS

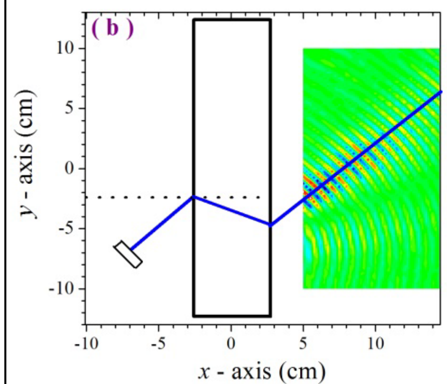
- Modeled realistic compliant coatings indicating a significant reduction in scattering.
- Tested reduction coatings in two geometric configurations, with three coating thicknesses in two types of coating material.
- Demonstrated scattering reduction of -7dB in near field data.

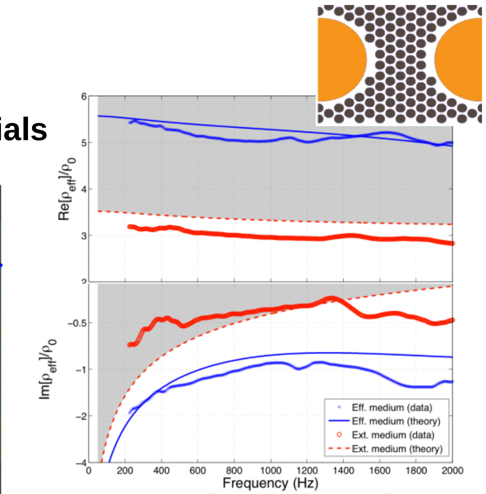
Extraordinary absorption by acoustic metamaterials
J. Sánchez-Dehesa, Univ. Politécnica de Valencia

OBJECTIVES

- Development of acoustic metamaterials for the control of acoustic scattering, absorption and focusing.
- Design artificial structures showing absorption enhancement with respect to their building units.
- Proof of concept demonstrations in airborne and aqueous environments.

Negative refraction by hyperbolic acoustic materials





Loss enhancement by multi-scale sonic Xtals

APPROACH

- Theory and characterization of hyperbolic acoustic materials based on lattices of perforated plates.
- Development of an algorithm to calculate the sound transmission through perforated cylindrical shells.
- Application of multiple scattering theory to multi-scale sonic crystals.
- Homogenization of losses in sonic crystals with large filling fractions.
- Full semi-analytical theory of the interaction of sound waves impinging on a metallic slit embedded in water.
- Theory and characterization of transverse flexural resonances in disks made of lossy poroelastic inclusions

ACCOMPLISHMENTS

- Demonstration of negative refraction and energy funneling by acoustic hyperbolic materials.
- Design, fabrication and characterization of lattices of perforated shells showing energy redirection and absorption enhancement.
- Sound absorption enhancement experimentally observed in multi-scale SC.
- Parametric characterization of lossy SC based on SC with high filling fractions.
- Demonstration of energy redirection by a slit in a metallic plate embedded in water.
- Experimental demonstration of absorption and negative mass density utilizing transverse flexural resonances in sub-wavelength aerogel disk samples.

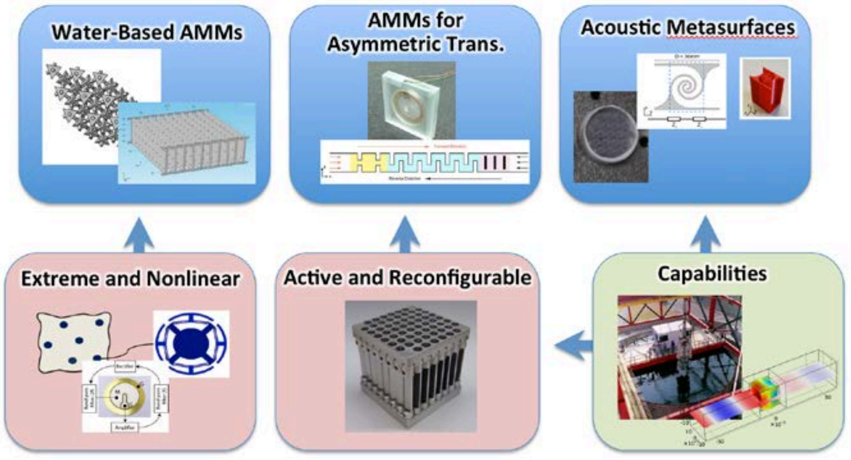
Expanding the Limits of Acoustic Metamaterials

Steven A. Cummer, Duke University

OBJECTIVES

- The broad goal of this MURI is to use an array of novel approaches to improve the range of effective material properties that can be created in 3D acoustic metamaterials employing subwavelength elements

The multi-group project targets several focused coordinated research topics (top), broad directions (bottom left), and the development of new measurement and simulation capabilities (bottom right).



APPROACH

- Combine cross-group coordinated efforts with the development of new approaches for novel material properties and functionality
- Current coordinated efforts on water-based metamaterials, asymmetric transmission materials, and acoustic metasurfaces

ACCOMPLISHMENTS

- Developed and fabricated two fundamentally different approaches for water-based acoustic metamaterials. Measurements are in progress.
- Demonstrated strongly asymmetric transmission in a thin (λ/10), nonlinear, active acoustic structure. Several other approaches are close to measurements.
- Designed, simulated, and experimentally demonstrated subwavelength-thickness acoustic metasurface lenses and diffraction gratings

0805-0825 Nanoplasmonic Metasurfaces on Graphene: Broadband Tunable Response and Antenna-Enhanced Mid-IR Modulators & Photodetectors

Federico Capasso, Harvard University

Graphene is emerging as a broadband optical material which can be dynamically tuned by electrostatic doping. However, the direct application of graphene sheets in optoelectronic devices is challenging due to graphene's small thickness and the resultant weak interaction with light. By combining metal and graphene in a hybrid plasmonic structure, it is possible to enhance graphene−light interaction and thus achieve in situ control of the optical response. We demonstrated an electrically-tunable coupled antenna array on graphene with a large tuning range (1100 nm, nearly 20% of the resonance frequency) of the antenna resonance wavelength in the mid-infrared (MIR) region. By incorporating these widely tunable metasurfaces into a sub-wavelength-thick optical cavity to create an electrically-tunable perfect absorber and by switching the absorber in and out of the critical coupling condition via the gate voltage applied on graphene, a modulation depth > 95% was achieved. Finally, antenna enhanced mid-IR photoconductive detectors with a responsivity of 0.4 volt/watt, 200 times larger than detectors without antennas, were demonstrated at λ= 4.5μm.

0825-0845 Device Applications of Metafilms & Metasurfaces

Mark Brongersma, Stanford University

Many conventional optoelectronic devices consist of thin, stacked films of metals and semiconductors. In this presentation, I will demonstrate how one can improve the performance of such devices by nano-patterning the constituent layers at length scales below the wavelength of light. The resulting metafilms and metasurfaces offer opportunities to dramatically modify the optical transmission, absorption, reflection, and refraction properties of devices. This is accomplished by encoding the optical response of nanoscale resonant building blocks into the effective properties of the films and surfaces. To illustrate these points, I will show how nanopatterned metal and semiconductor layers can be used to enhance the performance of photodetectors, solar cells, and enable new imaging technologies.

0845-0905 Metamaterial Surfaces Integrated with Photonic Devices

Dennis Prather, University of Delaware

This presentation will discuss our work in using metamaterial surfaces integrated with photonic devices to realize a thin veneer of sub-wavelength antennas that act like nerve endings in the skin of a living creature. They are designed to cover most of the aircraft surface to sense and manipulate the electromagnetic environment in the full k-w space at frequencies spanning from DC to hundreds of GHz. We will cover our design and fabrication of the metamaterial surface and the integration of functional devices, such as high frequency modulators and high power photo-diodes, that enable full spatial and frequency coverage for emerging military applications.

0905-0925 Si-Based Active Metamaterials for High-Density Integration

Luca Dal Negro, Boston University

This work is aimed at developing novel Si-based metamaterials for broadband emission and tunable nonlinear optical generation on a chip. In particular, I shall discuss the engineering of low-loss conductive dielectrics with tunable negative permittivity for active epsilon-near-zero (ENZ) and hyperbolic media with enhanced light-matter interaction across the 1-2 micron spectral range.

0926-0928 Structured Metasurfaces: Resonant Excitation of Symmetry-Prohibited Diffraction Orders and Antireflection Coatings

Joshua R. Hendrickson, AFRL/RYDH

Two remarkable properties of structured metal surfaces will be discussed in this presentation. The first is resonant diffraction into a symmetry prohibited order of a metal grating. Fourier analysis implies that a half wave symmetric grating, such as a 50% duty cycle rectangular grating, does not contain any even order harmonics. However, by exciting a surface plasmon polariton, a two-step diffraction process is possible and resonant excitation into an even diffraction order is not only possible, but, in fact, can be stronger than that of all symmetry allowed orders combined, exceeding more than 70%. In the second part of the presentation, a subwavelength antireflection coating consisting of a periodic array of metal crosses with a thin dielectric spacer layer on top of a high refractive index substrate will be illustrated. By passively tuning the plasmon resonance, complete control of the phase and reflection coefficient at the surface is possible, allowing for wide angle anti-reflection. Such a coating is superior to standard quarter wave and multi-layer stacks which can be quite thick, especially at longer wavelengths, and are highly dependent on the specific refractive index properties of the layers, unlike our metasurface based device.

0928-0930 Plasmonic Nanostructures by Design

Xiaoqin (Elaine) Li, University of Texas - Austin

The properties of individual semiconductor and metallic nanoparticles have been extensively investigated. When these nanoparticles are controllably arranged in a particular geometry, new and fascinating properties emerge. We use an AFM nano-manipulation method to manipulate individual metallic, dielectric and semiconductor nanoparticles to assemble designed plasmonic nanostructures with novel functionalities. I shall represent our most recent experiments on coupling a single semiconductor quantum dot to a plasmonic nanoparticle. We demonstrate that a single quantum dot can be used to induce plasmonic cavity transparency close to 50%. This demonstration also opens the door to versatile single photon sources with different photon statistics in different spectral regions.

0930-0932 Epitaxial Grown Indium Plasmonic Nano-structures on Semiconductor Gain Medium

Galina Khitrova, University of Arizona

Lately there has been much interest in the epitaxial growth of metals, for example silver, for meta-material plasmonic structures. Amazingly we have discovered the distribution in size of molecular

beam epitaxy grown self-assembled Indium pancakes is narrow enough to provide a plasmonic resonance tunable from 1.5 μm for 150 nm diameter pancakes to 8 μm for 1500 nm diameter pancakes. The beauty of our system is that in the same high vacuum chamber we can first grow semiconductor gain material (for example quantum wells and quantum dots) before changing parameters and depositing high-purity metallic indium nano-structures. The fact that indium also becomes superconducting at 3.4K offers another interesting possibility of obtaining a single photon detector from a hybrid superconducting-semiconductor structure. This work is done in collaboration with Karlsruhe Institute of Technology and Joshua Hendrickson from Wright-Patterson Air Force Base.

0932-0934 Semiconductor Based 2D Photonic Crystal Metasurfaces and 3D Optical Metamaterials for Integrated Photonics

Weidong Zhou, University of Texas - Arlington

I shall first report on the progress and challenges associated with Fano resonance in 2D photonic crystal semiconductor meta-surface-based membrane photonics, including perfect reflectors and absorbers, as well as extremely high-Q optical filters and ultra-compact membrane lasers. Then, I shall discuss the strategies and processes in semiconductor-based 3D optical metamaterial fabrication for applications in active optoelectronics and integrated photonics.

0934-0936 Tailoring Magnetic Nanomaterials for Electromagnetic Wave Absorption

Chao Wang, Johns Hopkins University

Electromagnetic wave absorbing materials play an important role in modern industry. They are used in portable electronic devices such as smart phones and mobile PCs to protect human bodies from exposure to electromagnetic pollution, which could interfere with cellular activities and raise the risk of getting involved in cardiac/vascular, cancer or neural illness. In defense, the surface of ships and aircrafts is painted with electromagnetic absorbing materials to reduce the radar cross section (RCS). This presentation will discuss our study of magnetic nanomaterials for electromagnetic wave absorption. Our research is built on the progress made in the past decades on the synthesis of magnetic nanomaterials (<10 – 100 nm) by wet–chemistry methods, which has enabled us to advance the materials and technologies for electromagnetic wave absorption. Synthetic conditions are explored for tuning the particle size and composition to tailor the magnetic properties in terms of saturation magnetization and coercivity. Permittivity and permeability of the nanoparticle assemblies are then characterized by vector network analyzers, based on which the electromagnetic wave reflection and absorption properties are derived.

0936-0938 Propagation of Longitudinal and Transverse Spatial Modes in Metamaterials

John S. Derov, AFRL/RYDP

Spatial dispersion has been observed in metamaterials. A combination of simulated and measured data are used to show the behavior of the longitudinal, transverse and incident wave in a split-ring wire post metamaterial. When the spatial modes are excited, three waves propagate through the

metamaterial: an incident, longitudinal, and transverse wave. The excitation and control of the spatial modes in a metamaterial will be presented, and the use of the longitudinal wave to compress the free space wavelength of the incident wave, along with the relationship between spatial dispersion and negative refraction will be discussed.

0938-0940 Perturbation of Surface Plasmon Resonance in Gold Films Using Graphene Layers

John S. Derov, AFRL/RYDP

A Kretschmann configuration was used to study perturbation in surface plasmon resonance gold films using graphene layers. The surface plasmon resonance of a gold film was characterized in the near infrared spectrum. A single layer of graphene was transferred to gold film and the surface plasmon resonance was characterized again to look at the change in the momentum required to excite the surface plasmon resonance. More graphene layers were added to the gold film to study the change in momentum to excite the resonance. The results of the measurements will be presented and discussed.

0940-0942 Near-to-Mid-Infrared Fluorescence Enhancement of Rare Earth Polytantalate Films Deposited on Random Gold Particle Films

Nicholaos Limberopoulos, AFRL/RYDP

Random gold nanoparticle films on sapphire were prepared using a scalable, high-throughput process that afforded particle resonance tunability of over 1 µm. Localized surface plasmon polariton (LSPP) resonances, in air, of 0.584 µm (FWHM 0.130 µm) to 1.581 µm (FWHM 1.9 µm) were obtained. Application of a higher refractive index coating shifts this resonance well into the mid-infrared region. A uniform 122 nm thick, rare earth polytantalate film, $Tb_{0.15}Y_{0.85}Ta_7O_{19}$, was sputtered onto the random gold nanoparticle films. Four wavelength bands were observed, stable over time, exhibiting fluorescence enhancement for these films relative to the same thickness film on clean sapphire: 1.52-1.67 µm, 1.69-1.86 µm, 2.24-2.54 µm, and 3.87-4.14 µm. The fluorescence enhancement factors were 5.87, 5.70, 5.82, and 5.82, respectively, indicating the $Y_{0.85}Tb_{0.15}Ta_7O_{19}$ is between 5.70 -5.87 times more fluorescent in the presence of gold particles with an LSPP extinction spectrum overlapping the rare earth fluorescence spectrum. In addition, thermal imaging in the 7-12 µm region of these same $Tb_{0.15}Y_{0.85}Ta_7O_{19}$ films on random gold nanoparticles indicated a substantial enhancement in the thermal emission of the rare earth films.

0942-0944 Meta-Conductors with Invisible Dopants

Mona Zebarjadi, Rutgers University

Carrier mobility is a key material parameter in determining the performance of semiconductor-based devices such as transistors, LEDs, solar cells, thermoelectrics, etc. Semiconductor materials are usually doped with external impurity atoms to provide the required level of carrier concentration (electrons/holes) for good electronic performance. These impurity atoms scatter the conduction carriers and limit their mobility. The aim of this research is to cloak the doping centers to minimize the deleterious effect of conventional doping. We have demonstrated theoretically the

possibility of electronic cloaking using artificial nanoparticles. The work will be extended to identify particles made of realistic materials and to identify more practical particles of larger sizes where transport is incoherent. Of interest are investigation of anisotropic materials, of multiple scattering of cloaked particles, and investigation of multilayered particles. We aim to demonstrate experimentally electronic cloaking using 2D devices (i.e., graphene and GaAs/AlGaAs 2D electron gas) while using artificial potentials imposed by means of gating. The results will be useful for device applications as well as for defect engineering.

1030-1055 Quantum Metaphotonics and Quantum Metamaterials – FY12 MURI

Rashid Zia, Brown University

At the quantum level, both the strength and nature of light-matter interactions are limited by the size mismatch between the optical wavelength and the electronic wave function of single emitters. Here, we will discuss how our MURI team is challenging these limits by integrating quantum emitters with optical metamaterials in two regimes. At one extreme, we are using the confined and enhanced fields from subwavelength cavities and resonant optical antennas to enhance microscopic light-matter interactions with single emitters. At the other extreme, we are exploiting the extended modes in epsilon-near-zero waveguides and antenna arrays to explore collective excitations in dense emitter ensembles. In this brief presentation, we shall highlight recent progress that spans from theory and materials research to device design, fabrication and characterization. Examples will show how metamaterial designs and nanophotonic concepts can be used to reexamine fundamental assumptions about light-matter interactions and expand the range of materials for solid state quantum optics.

1055-1120 Innovative Use of Metamaterials in Confining, Controlling and Radiating Intense Microwave Pulses - FY12 MURI

Edl Schamiloglu, University of New Mexico

The FY12 AFOSR Transformational Electromagnetics MURI program is led by the University of New Mexico (Edl Schamiloglu, PI) and includes MIT (Richard Temkin, PI), Ohio State University (John Volakis, PI), UC-Irvine (Alex Figotin, PI), and Louisiana State University (Robert Lipton, PI). The goal of this consortium's research is to engineer novel dispersion relations using metamaterials in order to explore electron beam/electromagnetic wave interactions that can lead to new amplifier concepts. As we are entering Year 3 of this program we have learned the following. The evolution of electromagnetic fields in metamaterial structures typically requires dozens of cycles of the RF radiation. This has made designing intense beam-driven experiments challenging since the accelerators available are relatively short pulse. MIT has explored a complementary split ring resonator-based backward-wave oscillator that is about to enter the experimental stage. The growth time for oscillations is a few 100 ns and their modulator has pulse duration of 1 μs. The University of New Mexico has designed a slow wave structure using an array of broadside-coupled split ring resonators that requires only a few nanoseconds to grow. This will be investigated using their two accelerators with pulse lengths of about 10 and 30 ns, respectively. Our recent results and the theoretical contributions of our partner universities will be summarized.

1120-1140 Metamaterial Apertures for Computational Imaging

David R. Smith, Duke University

We have designed and implemented a stand-alone microwave imaging system based on a frequency-dispersive, metamaterial aperture. The metamaterial aperture consists of a parallel-plate waveguide in which is launched a cylindrical wave that excites an array of patterned, resonant, complementary metamaterial elements in the upper plate. The structure radiates a set of complex field patterns whose spatial patterns throughout the scene vary as a function of frequency. With a simple frequency sweep, a three-dimensional image of the scene can be reconstructed using standard computational imaging approaches. The metamaterial imager system is capable of resolving human-sized targets, and is under consideration for threat detection applications. As the low frequency imaging work has transitioned to more applied programs, we are now in the process of developing the tools and platforms that will allow the computational imaging concept to be transitioned to infrared and visible wavelengths. At these wavelengths, the system architecture and underlying components are considerably distinct from the microwave and millimeter wave apertures, allowing for a wider variety of opportunities. We will discuss the film-coupled nanoparticle configuration as one approach to the assembly of novel apertures for imaging and optical beam-forming.

1140-1200 Compressive Sensing and Enhanced Detectors with Plasmonics and Photonic Nanojets

Augustine Urbas, AFRL/RXAP

Detecting optical signals in the mid and long wave infrared are significant to a range of Air Force technologies and drive the research to increase performance and functionality. Both spectral and spatial information is obtained in images with hyperspectral imagers. New challenges arise as detector pixel counts increase and the information desired from image data is more widely used. Limitations on data communication rates provide a bottleneck for acquiring and processing the increasingly large data sets. Compressive sensing may allow for the acquisition of more efficient data with higher information content, while preserving mission utility. Our research develops a combined method to integrate plasmonic and micro-optical elements onto detector structures which can both improve their performance and provide a means to introduce compressive sensing methods. By coupling a variety of simulation environments which cover the optical, plasmonic, and electronic domains, we can efficiently enhance the detector function and performance for a wide range of designs and incorporate compressive sensing into the design loop. We will present the results of several design studies and experimental verification of the modeled device performance.

1300-1320 Metasurfaces for Wavefront and Polarization Control

Anthony Grbic, University of Michigan

Metasurfaces are surfaces textured at a subwavelength scale to achieve tailored electromagnetic properties. They fall into two broad categories. The first class of metasurfaces manipulate electromagnetic wavefronts incident from free space. This type of metasurface tailors the wave transmitted through it, or reflected from it. The second class of metasurfaces guide or radiate

waves. The metasurface acts as either a waveguiding structure or supports leaky waves that radiate directive radiation patterns. This talk will describe advancements in both types of metasurfaces.

Reflectionless metasurfaces that can steer, focus and manipulate the polarization of transmitted electromagnetic waves will be presented. In addition, a new approach to designing 2D anisotropic, inhomogeneous media will be introduced. The design methodology allows the design of 2D media that support desired spatial distributions of phase progression (wave vector) and power flow (Poynting vector direction). Its utility in the design of metasurfaces will be demonstrated through different design examples.

1320-1340 Photonic Crystals As Topological Resonators

Roberto Merlin, University of Michigan

It is well known that defects, such as holes, within an infinite photonic crystal can sustain localized resonant modes within the photonic forbidden band. Here we prove that finite, defect-free photonic crystals (PCs) behave as mirrorless resonant cavities for frequencies within but near the edges of an allowed band, regardless of the shape of their outer boundary. Preliminary experimental data on two-dimensional PCs will also be shown. The resonant modes are extended, surface-avoiding states that may lie inside or outside the light cone. Independent of the dimensionality, quality factors and finesses are on the order of, respectively, and where λ is the vacuum wavelength and $L >> \lambda$ is a typical size of the crystal. Similar topological modes exist in conventional Fabry-Pérot resonators, and in plasmonic media at frequencies just above those at which the refractive index vanishes.
$()_{3}/L\lambda\ /,L\lambda$

1340-1400 Sub-Diffractional Focusing of Infrared Polaritonic Rays in a Natural Hyperbolic Material Hexagonal Boron Nitride

Dmitri N. Basov, University of California at San Diego

Hyperbolic electromagnetic media defined by the opposite signs for in-plane and out-of-plane dielectric tensors reveal remarkable optical and thermal phenomena. Hyperbolic response can be achieved in various classes of metamaterials. Recent experiments carried out at UCSD established that a layered insulator: hexagonal boron nitride (hBN) reveals hyperbolic response at mid-infrared frequencies, and also supports propagating phonon polaritons [Dai et al. Science 343, 1125 (2014)]. New data show that hBN can act as a "hyperlens" and as a multi-mode waveguide. Hybrid structures comprised of hBN and graphene atomic layers present opportunities for tunable polaritonic response.

1420-1440 Manipulating THz Light with Mass of Massless Graphene Electrons

Donhee Ham, Harvard University

One of the most celebrated features of graphene is the behavior of individual electrons as massless relativistic particles. However, we recently demonstrated non-zero mass collectively emerging from the massless graphene electrons [1] by measuring graphene kinetic inductance that represents the collective electrons inertial reluctance to accelerate. This collective mass offers new exciting vistas

in manipulating THz light in artificial ways. As graphene kinetic inductance per unit length is orders-of-magnitude larger than magnetic inductance per unit length, graphene can produce a given value of inductance in an extremely small area. Exploiting this effect, we are developing ultra-subwavelength artificial materials from graphene which can manipulate THz light in non-conventional ways. Examples include left-handed, electro-kinetic transmission structures with gigantic negative refractive indices [2], ultra-subwavelength plasmonic bandgap materials [3,4], near-field 2D antennas and nonlinear THz detectors. This work entails advanced graphene device synthesis, such as interfacing graphene with other atomic-layer materials to create chemical cleanness and atomic flatness. Additionally, as the collective mass of graphene electrons can be greatly altered by bias, the metamaterials are tunable by voltage.

1440-1500 A Novel Mechanism to Suppress Losses based on Bichromatic Irradiation

Alkim Akyurtlu, University of Mass. at Lowell

The theory for reduction of optical losses, based on the coupling of two waves in a nonlinear (non-Ohmic) conductive medium will be introduced. In this mechanism, the coupling of two waves, the probe wave (p) and the support wave (s), takes place if waves have a parametric frequency ratio, $\omega p:\omega s=2:1$. The carriers in the conduction band interact with both waves of the bichromatic irradiation and provide the parametric coupling. The effect of optical loss reduction is due to the flow of energy from the high-energy support (s) mode into the low-energy probe mode (p). With adjusted irradiation parameters, the flow of energy compensates the optical losses in the probe mode. This presentation will provide a detailed analysis of the loss suppression mechanism and an experimental demonstration for the optical loss suppression for both metals and semiconductors within the mid-IR frequency range. The optical materials which were studied include a dispersionless semiconductor, e.g. ZnTe, and a highly dispersive Au thin film. When the specific conditions are satisfied, the optical losses, in the probe wave, were shown to be significantly reduced.

1540-1600 Optical-Antenna-Enhanced Spontaneous Emission

Ming Wu, University of Cal. at Berkeley

Antennas emerged at the dawn of radio for concentrating electromagnetic energy to a small volume $<< \lambda^3$, allowing for nonlinear radio detection. Such coherent detection is essential for radio receivers, and has been used since the time of Hertz. Conversely, an antenna can efficiently extract radiation from a sub-wavelength source, such as a small cellphone. Similarly antennas can accelerate spontaneous emission from a small quantum dot or molecule, whose emission rate can become faster than stimulated emission. Antennas interact equally with real electromagnetic fields, as well as quantum zero-point field fluctuations that are responsible for spontaneous emission. Regrettably, antenna physics is hardly addressed within the Physics curriculum. Whether from Jackson, the Feynman Lectures, or Yariv, it's hard to learn the true beauty of antenna science. We will give a brief pedagogic description of the three most important parts of antenna physics:

1. The Radiation Resistance;
2. The Electromagnetic Capture Cross-Section;
3. The Wheeler Limit on antenna Q.

These properties are encapsulated in an antenna equivalent circuit that provides us with physical understanding. Since antennas are intended to work at frequencies well below the plasma frequency, plasmonic effects are usually a minor perturbation to antenna physics, only contributing some kinetic inductance to the underlying antenna properties.

1600-1620 Metamaterial-Based Nonreciprocal Structures

Nader Engheta, University of Pennsylvania

In this presentation, I will give the highlights of our efforts supported by this grant in recent months. Under this grant we have been studying how metamaterials can provide novel ways to enhance, alter, and offer unconventional nonreciprocal and "one-way" behaviors in light-matter interaction. We have been extensively exploring the following topics: nonreciprocal light extinction, in which properly designed structures may exhibit distinct absorption spectra for different directions of propagation, enhanced near-field Faraday rotation in the vicinity of subwavelength nanostructures, unconventionally enhanced far-field nonreciprocity, simulating atoms with light inspired by the nonreciprocal magnetically active nanostructures showing Zeeman-like resonance splitting, optical isolation using nonlinearity (i.e., optical "diode"), all-passive nonreciprocal metasurfaces without using any biasing magnetic and/or electric fields, topologically protected surface states using metamaterials in which the TE-polarization surface wave propagates in one way while the TM-polarization surface wave propagates the opposite direction (i.e., photonic analog of topological insulator), and nonreciprocal light-line crossing and related items. We have obtained exciting results for all these projects. I will present an overview of the highlights of our recent results.

1620-1640 Reconfigurable Infrared Phased-Array Metamaterials

Jon Schuller, University of California at Santa Barbara

The ability to engineer the scattering *phase* of metamaterial constituents offers tremendous potential for constructing new classes of beam steering, shaping, and focusing technologies. Current methods for engineering phase rely on static geometry-based effects. In this YIP program we are searching for ways to *dynamically* tune the scattering phase of infrared semiconductor nano-antennas. We fabricate spherical silicon nanoparticles via femtosecond laser ablation and demonstrate size-dependent magnetic dipole (MD) resonances throughout the infrared frequency range. We experimentally demonstrate that the MD resonance frequency shifts with doping, according to simple Drude models of free-carrier refraction. Using a combination of theoretical and analytical calculations, we show that dynamically tuning free-carrier concentration can enable reconfigurable optical antennas and meta-surfaces. In particular, we demonstrate a meta-surface design where optical or electrical pumping can tune the transmission phase by 2π while maintaining near-unity transmission amplitude. Such dynamic tuning will enable reconfigurable photonic devices based on optical antenna and metamaterial concepts.

1640-1700 Fundamental Properties and Practical Applications of Active Microwave Metamaterials Incorporating Gain Devices

Hao Xin, University of Arizona

Introducing active gain or negative impedance in a metamaterial can theoretically overcome the intrinsic loss and narrow bandwidth issues of passive metamaterials. However, obstacles remain to realize a lossless, wideband and stable metamaterial. Our work investigates a proper method of analyzing and understanding active metamaterials with gain. This method is validated by analyzing and simulating a 45 degree wedge system with a normal incident Gaussian beam. This wedge comprises the complex media with finite boundaries, therefore is more realistic and reasonable compared to a semi-infinite case. Good agreement between analytical and numerical simulation is achieved. Stability is another challenging issue in realizing active metamaterials. Stability analysis methodology using return difference (or Normalized Determinant Factor) method based on Bode's feedback theory is developed. A circuit model is initially built and a parametric study is conducted to find the stable region and parasitic effects. Case study of an electrically small dipole antenna matched with negative impedance circuits is conducted. In addition, an experimentally demonstrated volumetric negative index structure with net gain will be presented. A refractive prism based on this structure also is simulated to validate the concept.